TPStream: Low-Latency Temporal Pattern Matching on Event Streams

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ABSTRACT
Complex Event Processing (CEP) has emerged as the state-of-the-art technology for continuously monitoring and analyzing streams of events in time-critical applications. The key feature in CEP is sequential pattern matching to detect a user-defined sequence of conditions on event streams. However, many CEP applications are not restricted to events only, but require native support for situations (aggregated event data lasting periods of time) and expressive temporal pattern matching among these situations. These important requirements regarding situations are not sufficiently addressed in the CEP literature so far.

In this paper we present TPStream, a novel event-processing operator for both deriving situations from event streams and detecting temporal patterns among situations. First, we provide a formal foundation of situations and TPStream. Then, we propose a low-latency algorithm for TPStream that delivers situations and temporal matches at the earliest possible point in time. Furthermore, we utilize a simple, yet effective cost model in order to adapt to changing workloads on the fly and with negligible cost for migrating operator states. The results of our experimental evaluation show that TPStream is capable of processing high-volume event streams with low latency and outperforms applicable CEP solutions from academia and industry.

1 INTRODUCTION
During the last decade, Complex Event Processing (CEP) has emerged to the technology of choice for analyzing massive streams of events in near real time. Typically, CEP systems detect composite (complex) events by combining, aggregating and filtering streams of simple or other composite events and report matches to registered event sinks. In turn, these sinks react to the detected event by triggering appropriate actions in a timely manner. CEP can be applied to a wide variety of application domains, including IT infrastructure monitoring, traffic monitoring, health care and financial applications.

Problem Statement: A noticeable fraction of currently available CEP systems is build upon point based temporal semantics. That is, each event is associated with a timestamp (e.g., the moment a measurement was made) and event streams are ordered accordingly. With only a single timestamp the expressible temporal relations between two events are limited to before/after/at the same time relationships. However, many real-world scenarios comprise the detection of complex temporal patterns among situations lasting for periods of time. Consider the following traffic-monitoring application:

Example: A traffic monitoring system is continuously receiving sensor data from connected cars (i.e., position, speed, acceleration). One of the systems goals is to notify drivers about potential dangers around their locations, such as an aggressively driving car. Among others, the American Automobile Association has identified the following two actions being indicators for aggressive driving¹: “Operating the vehicle in an erratic, reckless, careless, or negligent manner or suddenly changing speeds” and “Driving too fast for conditions or in excess of posted speed limit”. From these definitions, a pattern to detect aggressive drivers could be stated as: A sharp acceleration followed by hard braking, both accompanied by a period of speeding.

Challenges: This example illustrates three key-features a solution for temporal pattern matching on instantaneous events should provide: (i) Situations are derived from point events on-the-fly, by identifying subsequences of the input stream for which the defined condition holds true (e.g., speed > 70 mph). Optional constraints can be applied to restrict the duration of situations. In addition to its validity (expressed as a time interval), a situation is enriched with meaningful summarizations of underlying events (e.g., the average speed of the speeding phase). (ii) The pattern language offers support for alternatives. That is, the order of the situations’ start and end points is not required to be fully fixed. Consider, for example, the two matches sketched in Figure 1: In the first match, the three defined situations overlap, while in the second match deceleration happens during the speeding situation. (iii) The pattern should be detected with the lowest possible latency. As depicted in Figure 1, both matches may be concluded at the beginning of the deceleration situation, since at this point in time speeding still holds true and the pattern allows any combination of their endpoints. Technically, this means the system should be able to conclude a successful match without exact knowledge about the validity of all situations.

State-of-the-Art: To the best of our knowledge, the only work on complex temporal relations in event stream pattern matching is the ISEQ operator [20]. However, ISEQ has several shortcomings concerning the desired features: First, the operator expects interval-events (i.e., situations) as input, leaving all aspects of (i) to an unspecified external entity. Being unaware of the origin of interval-events severely limits the operator in processing power (in terms of plan optimization) and most importantly renders a detection with the lowest possible latency (iii) impossible since there is no way to directly assess an incomplete situation or indirectly manipulate the building of a situation through constraints.

¹http://www.iii.org/fact-statistic/aggressive-driving
Second, a temporal pattern is specified using a conjunction of endpoint relationships (i.e., an ordering on start (ts) and end (te) of intervals). This way, alternatives are expressed by omitting one or more endpoints. For example, the pattern $A \cdot \text{ts} < B \cdot \text{ts} < A \cdot \text{te} \leq B \cdot \text{te} \lor A \cdot \text{ts} < B \cdot \text{ts} < B \cdot \text{te} < A \cdot \text{te}$ on two situations $A$ and $B$ is expressed as $A \cdot \text{ts} < B \cdot \text{ts} < A \cdot \text{te}$. Hence, disjunctions like $A \cdot \text{ts} < B \cdot \text{ts} < A \cdot \text{te} \lor B \cdot \text{ts} < A \cdot \text{ts} < B \cdot \text{te} < A \cdot \text{te}$ are not expressible in a single query. Instead, they require multiple queries in an approach without any specified optimization component to detect shared processing opportunities. Finally, ISEQ relies on auxiliary index structures and punctuation mechanisms for efficient query execution, complicating the integration into existing systems.

**Straw Man’s Approach:** Besides ISEQ, we identified two approaches to solve the task of temporal pattern matching with point event streams. Thus, we can provide a point of comparison to CEP systems featuring pattern matching via regular expressions or equivalent techniques. The first approach works in two phases: In the first phase, a pattern matcher is deployed for each defined situation, computing its duration (start/end timestamp) and the desired aggregates. Technically, this means matching patterns of the form $\exists S \cdot 15 \cdot S \cdot 15$ with $S$ being derived from the input stream using the situation’s condition (e.g., speed $> 70$ mph). This results in a dedicated stream per defined situation. Each of these streams is ordered according to the end timestamp, which allows to map the temporal pattern to a sequence of situations (reflecting the order of end timestamps, possibly containing alternatives). In the second phase, a dedicated pattern matching operator is used to find all matching sequences, whereby the proper ordering of start timestamps is checked via additional predicates. Even though this approach satisfies requirements (i) and (ii), it fails to produce early results (iii), because, just like in ISEQ, situations are fully derived before they are available for pattern matching.

The second approach uses a single pattern matching operator and expresses the temporal pattern as a single sequence of point events. To express temporal overlaps, the conditions of all involved situations must be connected via a logical AND. For example, acceleration overlaps Speeding is expressed as $A \cdot B + C$ with the following conditions: $A: \text{accel} > 8 \text{ m/s}^2$, $C: \text{speed} > 70 \text{ mph}$ and $B: A \land C$. Since patterns are expressed on the granularity of events, early results (iii) are achieved, by simply omitting the last portion of the pattern. At the same time summarizations of single situations and the validation of duration constraints (i) are left to a post-processing step, since situations are disassembled to express temporal overlaps.

**Solution:** We present TPStream, a holistic operator for complex temporal pattern matching on point event streams. Compared to the presented approaches, our contributions are:

- **TPStream** is the first CEP operator to closely couple derivation of situations with pattern matching, enabling match detection at the earliest possible point in time.
- We also improve upon existing work on temporal pattern matching (e.g. ISEQ) by allowing arbitrary alternatives and duration constraints in pattern definitions.
- We introduce an optimizer component for interval-based pattern matching which continuously adapts its execution strategy to deal with fluctuating data rates and changes in the data distribution of incoming streams.
- TPStream provides native query support for temporal pattern matching, making it easier to formulate and read temporal patterns in comparison to most existing CEP solutions relying on a straw man’s approach.
- Unlike ISEQ, the operator and its low latency optimizations can easily be implemented in commonly available point-based systems, because time-intervals are used only internally and results are again point event streams.
- In experiments, we show our latency improvements and the performance limits of two existing CEP solutions from academia and industry when handling situations. We present that TPStream can outperform these systems by an order of magnitude and that alternatives, which have great impact on the performance of sequential pattern matching, influence TPStream’s matching performance only marginally.

The rest of the paper is organized as follows. Section 2 reviews related work, before we introduce TPStream’s query language in section 3. In section 4 we model all aspects of TPStream in an algebra. Efficient evaluation strategies, the algorithm for low-latency matching and our optimization techniques are presented in section 5. We evaluate the performance of TPStream in section 6 and conclude this paper in section 7.

2 RELATED WORK

So far, native ways to work with situations in systems capable of CEP have not been sufficiently addressed. Nevertheless, the concept can be related to working with time intervals, aggregating information and performing temporal joins, all of which have seen recent contributions. Since these are broad areas, we will loosely group the most relevant approaches under three headlines: Event Pattern Matching, Context/State in CEP and Spatio-Temporal Database Systems.

**Event Pattern Matching:** Systems capable of CEP (e.g. [3, 9]) are generally closely associated with a pattern matching operator. [27] features a discussion on the several different semantics of the operator and a recent survey [12] covers several implementations, that employ different techniques such as NFAs or Graphs, each featuring their own unique optimization techniques. Regardless of specific details, most approaches focus on data referring to points in time and thus lack native capabilities to query complex relations between time intervals as stated in [2] - a crucial aspect for dealing with long-lasting situations. Cayuga [8], ZStream [22] and Microsoft StreamInsight [1] are well-known approaches that associate time intervals with data, showcasing the interest in working with interval-based events. ZStream in particular shares similarities with our join-based, adaptive processing approach for pattern matching. However, each of the respective pattern languages is based around a strictly sequential relation (interval $i$ ends before interval $j$ begins) and/or explicitly order-independent relations (conjunction, disjunction). Not only does this limit their respective algorithmic support for complex temporal relations, but, just like point-based systems, formulating derivation queries naturally leads to the straw man’s approach mentioned above using Kleene Operators (or FOLDS in [8]). As we will show in our experiments, this approach results in significant performance deficiencies.

**Context/State in CEP:** There has been recent work on introducing contexts into a CEP environment. CAESAR [23] associates queries to long-lasting context windows, detects them from incoming events as soon as they start and suspends queries of inactive contexts. Similarly, contexts in [11] are used to group up event types to process them together. While contexts and
Table 1: Allen’s Interval Algebra

<table>
<thead>
<tr>
<th>Relation (R)</th>
<th>Equivalent (R)</th>
<th>Visualization</th>
<th>Definition (δp)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a before b</td>
<td>B after a</td>
<td></td>
<td>A t&lt; A te &lt; B t&lt; B te</td>
</tr>
<tr>
<td>A starts b</td>
<td>B started-by A</td>
<td></td>
<td>A t = B t &lt; A te &lt; B te</td>
</tr>
<tr>
<td>A meets b</td>
<td>B met by A</td>
<td></td>
<td>A t &lt; B t = B te &lt; B te</td>
</tr>
<tr>
<td>A overlaps b</td>
<td>B overlapped by A</td>
<td></td>
<td>A t &lt; B t &lt; A te &lt; B te</td>
</tr>
<tr>
<td>A during b</td>
<td>B contains A</td>
<td></td>
<td>B t &lt; A t &lt; B te &lt; A te</td>
</tr>
<tr>
<td>A finishes b</td>
<td>B finished by A</td>
<td></td>
<td>B t &lt; A t = B te &lt; A te</td>
</tr>
<tr>
<td>A equals b</td>
<td>B equals A</td>
<td></td>
<td>A t = B t = A te = B te</td>
</tr>
</tbody>
</table>

situations are related concepts, the key difference is that contexts are purposefully decoupled from events. Therefore, it is not possible to query the relation of different contexts to each other. In contrast, TPStream focuses on efficient, adaptive and low-latency implementuations of those temporal relations. Likewise, work on states [18] and on aggregating windows [14, 17] focuses on derivation, but lacks interval relations [2] or pattern matching.

Spatio-Temporal Database Systems: The spatial databases community studied the problem of spatio-temporal pattern queries (STPQ) in trajectory databases [10]. In general, these approaches cannot be directly applied to an event processing environment, because they are based on top of a persistent trajectory database model, where movement histories are already stored and indexed in the database. However, the design of [25] in particular served as a foundation for our proposed TPStream operator as TPStream adapts similar concepts of temporal predicates and constraints. Furthermore, our evaluation method is related to temporal joins (see [13] for an excellent survey), but as most of the work is not based in stream processing, unique and important issues such as continuously arriving data, continuous query optimization and early result detection are overlooked. In comparison to join algorithms on streams [6, 15] as well as adaptive approaches [5], TPStream combines both the derivation of situations and the definition of patterns. Thus, the operator can offer new techniques for early result detection unique to CEP-style pattern matching.

3 QUERY LANGUAGE

In order to express temporal relations between situations, we adopt Allen’s Interval Algebra [2] depicted in Table 1 for two generic intervals A and B. Each interval has a starting point (ts) and an ending point (te), resulting in a total of four points. te is the first point in time when the interval is not valid, i.e. the interval is half-open. The relation (R) between A and B is represented through the relation between these four points as given by the definition (δp). As an example depicted in Table 1 A before B means the interval A ends before the interval B begins. Similarly, A during B means A happens during B, because A ts and A te are between both points of B. We introduce the TPStream query language by formulating and explaining the query to detect aggressively driving cars from the introductory example in Listing 1.

The operator works on streams containing data referring to points in time. In the case of aggressive drivers, we work on a singular stream CS, providing sensor data from cars, which is specified as an input (FROM). This stream is partitioned by the car_id to evaluate each driver individually (PARTITION BY). The important aspect of deriving situations from the stream is handled in the DEFINE clause: The derived situation is represented with the symbol A, the condition CS.accel > 8 m/s² and the (optional) duration constraint AT LEAST 5s, while speeding and deceleration are defined by B and C respectively. The derived situations are analyzed with a PATTERN. For aggressive drivers, an acceleration (A) may meet, overlap, start or occur during a phase of speeding (B). These are alternatives in the pattern definition, separated with semicolons in the query language. The same applies for deceleration (C) and speeding (B). The pattern is fulfilled if at least one of each alternatives is true. We apply a window condition on the evaluation period (WITHIN), specifying that the pattern should only be searched within situations derived in the past 5 minutes. Finally, in case of a match, we RETURN aggregated results from each situation, in this case the car_id and the average speed.

3.1 Expressiveness

Most common CEP systems define patterns based on symbols connected via regular expressions. Specific extensions, like aggregations, put the expressiveness of those languages between regular and context-free grammars [27]. However, only ISEQ provides a native way to process patterns based on temporal relations. This deficit is also reflected in the respective languages.

By design, TPStream can express all temporal relations (and unlike ISEQ alternatives among them) in a single query. In contrast, a single pattern matching query in CEP systems is designed to detect a sequence, i.e., a before relation. Nevertheless, as shown by both straw man’s approaches in our introduction, in a system supporting Kleene-closure it is possible to express other temporal relations through either multiple queries (decoupling derivation and detection) or a single query (without aggregation capabilities and the validation of duration constraints). Thus, our language does not express more than the full language of other systems.

Instead, we focus on enabling the user to express complex temporal patterns in a single, readable and maintainable query via the widely-known interval algebra (Table 1). For this purpose, we made two notable design choices that differ from some sequence-based approaches. First, some languages [27] allow to skip events while matching. In contrast, we derive the longest possible contiguous sequence of events, because this aligns well with the idea of long lasting situations and avoids ambiguity whether a situations is still ongoing during other events. Second, some languages [9] allow symbols to access aggregates of other symbols. Due to ambiguity in the expected results when dealing with situations, we do not allow this. For example, consider modifying the definition for symbol B in Listing 1 to B AS CS.speed > max(A.speed). Then, for A overlaps B it is unclear whether max(A.speed) is accessed when A finishes, when B starts or is continuously monitored for each B. For a precise presentation of our approach, we chose those two concessions and will work on mitigating them in the future.
We would also like to sketch that, apart from those concessions, it is possible to express a purely sequence-based pattern with TPStream: A sequence can be expressed with a before relation and the implicit ongoing nature of situations can be eliminated with a duration constraint. Nevertheless, the basis for our implementation [19] features a standard sequence-based pattern matching operator that is optimized and thus preferable for this purpose. Similarly, our implementation can be easily integrated into other systems, because TPStream consumes and produces point-based event streams. In conclusion, this means that we do not change the expressiveness of other approaches, but by extending a query language with Allen’s Interval Algebra, our benefits can be almost universally adopted.

4 ALGEBRA

The goal in designing TPStream is to develop an operator capable of continuously deriving situations from a stream of events and relate those situations to each other. To achieve this, we need to be able to express both the derivation and relation. For this purpose, we will formally model those aspects (streams, data, deriving situations and temporal pattern matching) in an algebra.

4.1 Stream Model

Definition 1 (Data Stream). A data stream \( D \) is a potentially unbounded sequence of data items \( \langle d_1, d_2, \ldots \rangle \) totally ordered by a relation \( <_D \). \( d_i \in D \) refers to the \( i \)-th data item in the stream according to that order and all data items are from the same domain \( D \). \( \diamond \) refers to an empty data stream.

In order to refer to multiple data streams, we will utilize the notation \( D^1, D^2, D^3, \ldots \) with \( D^i = \langle d^i_1, d^i_2, \ldots \rangle \), i.e. a superscript labels separate streams, while a subscript refers to the order within a stream. For the sake of simplicity and legibility, we will generally assume that each item in a data stream is unique and refer to previous work on the matter of handling potentially equal elements [8]. \( \diamond \) is mainly used to specify the case of no output in upcoming definitions.

Definition 2 (Continuous Subsequence). Based on a data stream \( D, D_{[i,j]} = \langle d_i, \ldots, d_j \rangle \) with \( i < j \) refers to a continuous subsequence containing every data item as it pertains to \( <_D \).

Definition 3 (Union). The union \( w \) of two data streams \( D^1 \) and \( D^2 \) both totally ordered with \( <_D \) results in a data stream \( D' \) with the same order \( <_D \):

\[
w(D^1, D^2) := D' = \langle d'_1, d'_2, \ldots \rangle
\]

such that \( D' \) contains each element from both \( D^1 \) and \( D^2 \). Analogous to set theory, the union of \( n \) data streams \( D^1, \ldots, D^n \) is abbreviated with the notation \( \bigcup_{i=1}^{n} D^i \).

4.2 Data Model

Our operator involves two kinds of data which we need to define: events and situations. In general, events refer to a notification that something happened instantaneously at exactly one point in time while situations span multiple points in time and contain aggregated information for that time period.

Definition 4 (Event). An event \( e \) is a pair \((p, t)\) consisting of a payload \( p \) and an event timestamp \( t \). \( p \) is from some domain \( D \) and \( t \) is from a discrete and totally ordered time domain \( T \). The validity of \( p \) is the instant \( t \).

Definition 5 (Situation). A situation \( s \) is a triple \((p, t, e)\) consisting of a payload \( p \) and two timestamps: \( ts \) (start timestamp) and \( te \) (end timestamp). \( p \) is from some domain \( D \) and \( ts \) and \( te \) are from a discrete and totally ordered time domain \( T \) with \( ts < te \). The half-open time interval \([ts, te)\) specifies the validity of \( p \).

Event streams are ordered by the event timestamp and will be represented with \( E \). Situation streams are ordered by the end timestamp of situations and will be represented with \( S \). We focus our efforts on presenting algorithms for streams with data arriving in-order and leave the adjustment to out-of-order data by adapting previous research on out-of-order pattern matching [7, 21] for future work.

4.3 Derivation

Situations are derived from event streams through aggregation and predicate evaluation. We will first formally define aggregation on continuous event subsequences before deliberating on predicates and how to derive situation streams.

Definition 6 (Aggregated Event Subsequence). An aggregate \( \text{agg} \) is applied to an event stream subsequence \( E_{[i,j]} \) by applying the aggregate \( \text{agg} \) to the events in the subsequence:

\[
\text{agg}(E_{[i,j]}) := (\text{agg}(e_i, \ldots, e_j), e_{i+1}, e_{j+1}, \ldots)
\]

When obvious from context, we abbreviate \( \text{agg} \) with \( \gamma \).

The result in Definition 6 technically already is a situation. However, for the derivation process as a whole, we want to discover situations for which a set of circumstances hold true. In order to provide an unambiguous process to identify these situations we are looking for the longest possible sequences for which these circumstances apply.

Definition 7 (Derived Situation). Situations are derived with a function \( \text{derive}_{\phi, \gamma, \tau} \), which aggregates information of a continuous event subsequence \( E_{[i,j]} \) by applying \( \gamma \) iff the events in \( E_{[i,j]} \) are the longest possible sequence of events to fulfill a given predicate \( \phi \) and the covered timespan is within the given duration constraint \( \tau := [d_{\min}, d_{\max}] \):

\[
\text{derive}_{\phi, \gamma, \tau}(E_{[i,j]}) = \begin{cases} \forall l \in [i, j]: \phi(e_l) \land \gamma(e_{i-1}) \land \gamma(e_{j+1}) \land (e_{j+1}, ts - e_i, ts) \in \tau \\ \phi(e_{i-1}) \land \gamma(e_{j+1}) \land (e_{j+1}, ts - e_i, ts) \in \tau \\ \text{otherwise} \end{cases}
\]

Example. Assume the query in Listing 1 derives a speeding situation for a car with the time interval \([2, 10] \). This means \( \text{CS.speed} \leq 70 \text{ mph} \) at \( t = 1 \) and \( t = 10 \) and in between those timestamps \( \text{CS.speed} > 70 \text{ mph} \). From an algebraic standpoint, assuming knowledge about the whole event stream, this aligns well with a natural interpretation: There are not multiple situations (e.g. \([2, 3], [2, 4], \ldots\)) but rather one continuous speeding phase which fulfills the duration constraint \( d_{\min} = 4s \) and \( d_{\max} = 30s \). For that reason and because it results in unique situations, we choose to derive the longest possible subsequence in Definition 7.

Definition 8 (Derived Situation Stream). The \( \text{deriveStream}_{\phi, \gamma, \tau} \) function derives a stream of situations from a given event stream \( E \) by applying the function \( \text{derive}_{\phi, \gamma, \tau} \) to all possible subsequences and unifying the results:

\[
\text{deriveStream}_{\phi, \gamma, \tau}(E) = \bigcup_{j} \bigcup_{i=1}^{j} \text{derive}_{\phi, \gamma, \tau}(E_{[i,j]})
\]

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Note that, due to assumption that each event in an event stream has a unique timestamp and the fact that \( \text{derive}_\phi, \gamma, \tau \) produces a stream of situations with disjoint time intervals. This implies, that the order of situations using start timestamps is the same as the order using end timestamps, resulting in a beneficial pattern for query processing [16]. Due to space limitations, we omit a formal proof here.

### 4.4 Pattern Matching

**TPStream** matches multiple situation streams to a temporal pattern and produces a result event stream according to the given definitions. A temporal pattern is composed of temporal constraints between situation streams, which in turn comprise multiple temporal relations between exactly two streams. In this section, we present formal definitions of these terms, the output of a successful match and ultimately the **TPStream** operator.

**Definition 9** (Temporal Relation). Given two situation streams \( S^A, S^B \), a temporal relation \( R^{A,B} \), defines a valid relationship between two situations \( s^A \in S^A \) and \( s^B \in S^B \) according to Allen’s Interval Algebra (cf. Table 1). \( s^A \) and \( s^B \) fulfill \( R^{A,B} \), if they satisfy the corresponding algebraic definition (\( \delta_k \)).

**Definition 10** (Temporal Constraint). A temporal constraint \( C^{A,B} \) between two situation streams \( S^A, S^B \) is a set of temporal relations \( \{R_1^{A,B}, \ldots, R_m^{A,B}\} \). Two situations \( s^A \in S^A \) and \( s^B \in S^B \) fulfill \( C^{A,B} \), if they at least fulfill one of the temporal relations.

In other words, temporal constraints allow to specify multiple valid relations between two situation streams, providing the desired flexibility in expressing alternatives.

**Definition 11** (Temporal Pattern). For any number of situation streams \( S^1, \ldots, S^m \), a temporal pattern \( (P) \) is a set of temporal constraints \( \{C_1^{i,j}, \ldots, C_m^{i,j}\} \). A temporal pattern is matched by a configuration \( \mathcal{C} = (s^1, \ldots, s^m) \), if \( \mathcal{C} \) satisfies every temporal constraint:

\[
\text{match}_P(\mathcal{C}) = \forall C_{i,j}^{i,j} \in P \colon \exists R_{i,j}^{i,j} \in C_{i,j}^{i,j} \colon \delta_{P_{i,j}}(s^i, s^j)
\]

**Example.** Consider the example query of Listing 1 and let \( s^A \) be an acceleration situation as defined by \( A \) and \( s^B, s^C \) be a speeding (B) and deceleration (C) situation respectively. The **TPStream** describes how pairs of situations in \( \mathcal{C} = (s^A, s^B, s^C) \) can relate to each other via temporal constraints: For \( s^A, s^B \) the temporal relation can be either \( A \) meets \( B \), \( A \) overlaps \( B \), \( A \) starts \( B \) or \( A \) during \( B \). It does not matter if acceleration overlaps speeding or if speeding contains acceleration. Both cases may lead to the result of detecting aggressive drivers. The temporal pattern on the other hand is a conjunction of temporal constraints: In order to match the pattern, each temporal constraint must be fulfilled.

**Definition 12** (Pattern Matching Output). A temporal pattern matching operator \( \text{PM}_{m,w,\gamma}(\mathcal{C}, P) \) matches the temporal configuration \( \mathcal{C} = (s^1, s^2, \ldots, s^m) \) to a temporal pattern \( P \). It aggregates the information of \( \mathcal{C} \) with some suitable aggregate \( \gamma \) and checks the window condition (cf. **WITHIN** clause):

\[
\text{window}(\mathcal{C}, w) = w \leq \max(s, ts) - \min(s, ts) \quad \text{for} \quad s \in \mathcal{C}
\]

The operator produces an output, if the temporal configuration matches the pattern during the specified window, i.e.:

\[
\text{PM}_{m,w,\gamma}(\mathcal{C}, P) := \left\{ \begin{array}{ll}
(\gamma(\mathcal{C}), \max(s, te)) & \text{if } \text{match}_P(\mathcal{C}) \land \text{window}(\mathcal{C}, w) \\
\emptyset & \text{otherwise}
\end{array} \right.
\]

Similarly to how we extended derived situations to derived situation streams (Definition 7 to 8), we can extend Definition 12 to situation streams:

**Definition 13** (TPStream). **TPStream**\(_{m,w,\gamma}\) matches multiple situation streams \( S^1, \ldots, S^m \) to a temporal pattern \( P \) by applying the corresponding pattern matching operator \( \text{PM}_{m,w,\gamma} \) to the cross product of the situation streams and unifying the results:

\[
\text{TPStream}_{m,w,\gamma}(S^1, \ldots, S^m, P) := \bigcup_{\mathcal{C} \in S^1 \times \cdots \times S^m} \text{PM}_{m,w,\gamma}(\mathcal{C}, P)
\]

Note that **TPStream**\(_{m,w,\gamma}\) results in an event stream and can thus easily be integrated into common CEP processing pipelines.

### 5 ALGORITHMS & IMPLEMENTATION

In this section, we present our algorithms and implementation details for detecting temporal patterns among streams of point events. Following the definitions from the previous section, the general architecture consists of two main components, as depicted in Figure 2. The **deriver-component** consumes events from the input stream and derives the defined situation streams. Then, those streams are passed to the **matcher-component**, which performs the actual pattern matching. In the following two subsections we will explain both components in detail. For the sake of simplicity we defer low latency detection to section 5.3 and initially wait for the end timestamp of derived situations before invoking the **matcher**. The last part of this section describes how **TPStream** computes efficient execution plans and dynamically adapts to changing workloads.

#### 5.1 Deriving Situations

Definition 8 introduced derived situation streams, using knowledge about the whole input-stream. To compute situation streams incrementally as new events arrive the **deriver-component** manages a buffer for ongoing situations (B) and the situation stream definitions (D). Algorithm 1 shows how they are used to derive situations on-the-fly. For each defined situation, 3 cases are checked: If there is no started situation on the buffer, but the predicate holds true, a new situation is started. Therefore, we compute initial values for all defined aggregates (e.g., \( p, \text{speed} \) for an \( \text{max}(\text{speed}) \) aggregate). Those values are bundled with the event’s timestamp and stored on the buffer (Lines 4.5). The
temporal validity of a started situation is prolonged, if the current event fulfills the predicate. In this case, the buffered aggregates are updated using the event’s payload \((p)\) (Lines 6-7). Finally, a situation is finished on the first event not satisfying the defined predicate. In this case, the situation’s end timestamp is fixed to the current time, it is added to the result-set \(R\) (provided it satisfies the duration constraint \(\tau\)) and the corresponding buffer slot is cleared (Lines 8-11). After updating the state of each situation stream, the result-set is passed to the matcher-component (Lines 12-13).

### 5.2 Matching the Pattern

The matcher implements an incremental version of Definition 13 \((TPStream_{\text{mc}})\). In other words, it detects matches on-the-fly as new situations are handed over from the derivier-component. The general idea is to employ a buffer for each situation stream and perform the pattern detection via a multi-way join between those buffers, using the temporal constraints as join-conditions. Recall that all situations within a stream are disjoint and thus imply the same order on both the start and end timestamps (Definition 8). We will use this fact to ensure efficient execution of the matcher component.

Each time the derivier distills new situations, Algorithm 2 is invoked: At first, expired situations are purged from the buffers (Line 1). Then, all returned situations are successively added to the working-set and for each of the new partial temporal configurations, the algorithm proceeds to the next step (Lines 9-11). Lines 6 and 7 intercept the evaluation, if the working-set already contains a situation for the current step, which accounts for situations passed as a parameter from Algorithm 2. In this case, the corresponding buffer is ignored and the step’s temporal constraints are checked directly. Finally, a match is detected if the working-set contains a situation from every buffer (Lines 1-5). The publishResult function consumes this working-set, assembles the result and pushes it into the output stream.

Algorithm 3 (invoked Lines 2-4). We force the new situation to be part of any successful match, by passing it as a parameter. This ensures the desired incremental creation of results, because we pass a new, not yet considered situation on every invocation.

The matching algorithm relies on a so called evaluation order, which we describe briefly upfront. An evaluation order determines the order in which situation buffers are joined and provides the required information for each processing step (a reference to the situation buffer and the set of temporal constraints to be fulfilled). Using this information and a partial temporal configuration \((\text{working-set})\), Algorithm 3 matches the temporal pattern as follows: In each step, the corresponding situation buffer is searched for situations satisfying all applicable temporal constraints (Line 8). Applicable means, that the counterpart of the constraint is already present in the working-set. Then, all returned situations are successively added to the working-set and for each of the new partial temporal configurations, the algorithm proceeds to the next step (Lines 9-11). Lines 6 and 7 intercept the evaluation, if the working-set already contains a situation for the current step, which accounts for situations passed as a parameter from Algorithm 2. In this case, the corresponding buffer is ignored and the step’s temporal constraints are checked directly. Finally, a match is detected if the working-set contains a situation from every buffer (Lines 1-5). The publishResult function consumes this working-set, assembles the result and pushes it into the output stream.

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Algorithm 3 (invoked Lines 2-4). We force the new situation to be part of any successful match, by passing it as a parameter. This ensures the desired incremental creation of results, because we pass a new, not yet considered situation on every invocation.
We first discuss how this is done for a single temporal relation before extending it to (multiple) temporal constraints. Recall that a temporal relation explicitly defines a relationship between all four endpoints of two situations. For instance, this is $A.t_s < B.t_s < A.t_e < B.t_e$ for $A$ overlaps $B$. Now, given an instance of situation $A$, we can obtain matching instances of $B$ by (i) issuing two range-queries on the buffer of $B$, using the timestamps of $A$ as boundaries and (ii) intersecting the results of those queries. For example, in relation $R_1: A.befor B$ and $R_2: A.befor C$ and $R_3: A.befor D$ and $R_4: D.during C$, ...

We receive our final result at the end of this section. We gained two implementation-relevant insights from the low-latency analysis. First, new matches can only be detected if a new situation starts or a situation ends. Second, only a subset of the derived situations can possibly produce a match at $t_d(P)$. Thus, the matching process can be delayed until a situation with at least one endpoint in $t_d(P)$ occurs without affecting the latency. We call those situations trigger situations since only they should trigger a performMatch call. These insights affect our algorithms in the following ways. Situations must be available for matching from their start on, which can easily be achieved by adjusting the derivation. Additionally, we need to determine for each situation stream if the derived situations are trigger situations. For trigger situations we need to identify the point in time to execute performMatch (at its start, end or both).

However, the following cases must be considered during the matching process. If a situation requires matching on both endpoints, care must be taken not to produce duplicate results. Further, started situations must not be visible to the matcher in all cases: If two situations are related via finishes or equals, they could be mistakenly matched, because their temporary end timestamps (i.e., the current time) are equal. On the other hand, if two situations are not explicitly related via a temporal constraint they may participate in a successful match, even if both end timestamps are unknown. To illustrate this, consider the following pattern on four situations ($A$, $B$, $C$, $D$): $A$ before $B$ and $A$ before $C$ and $A$ before $D$ and $D$ during $C$ OR $C$.

<table>
<thead>
<tr>
<th>Relation (R)</th>
<th>Definition ($t_d$)</th>
<th>$t_d$ (R)</th>
<th>Prefix-Group (G)</th>
<th>$t_d$ (G)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A before B</td>
<td>$A.t_s &lt; A.t_e &lt; B.t_s &lt; B.t_e$</td>
<td>$B.t_s$</td>
<td>$A.t_s &lt; A.t_e &lt; B.t_s$</td>
<td>$B.t_s$</td>
</tr>
<tr>
<td>A meets B</td>
<td>$A.t_s &lt; A.t_e$ OR $B.t_s &lt; B.t_e$</td>
<td>$B.t_s$</td>
<td>$A.t_s &lt; A.t_e$ OR $B.t_s$</td>
<td>$B.t_s$</td>
</tr>
<tr>
<td>A starts B</td>
<td>$A.t_s &lt; B.t_s &lt; A.t_e &lt; B.t_e$</td>
<td>$B.t_s$</td>
<td>$A.t_s &lt; B.t_s$</td>
<td>$B.t_s$</td>
</tr>
<tr>
<td>A equal B</td>
<td>$A.t_s &lt; B.t_s &lt; A.t_e$ OR $B.t_s &lt; B.t_e$</td>
<td>$B.t_s$</td>
<td>$A.t_s &lt; B.t_s$</td>
<td>$B.t_s$</td>
</tr>
<tr>
<td>A started-by B</td>
<td>$A.t_s &lt; B.t_s &lt; A.t_e$</td>
<td>$B.t_s$</td>
<td>$A.t_s &lt; B.t_s$</td>
<td>$B.t_s$</td>
</tr>
<tr>
<td>A overlaps B</td>
<td>$A.t_s &lt; B.t_s &lt; A.t_e$ OR $B.t_s &lt; B.t_e$</td>
<td>$B.t_s$</td>
<td>$A.t_s &lt; B.t_s$</td>
<td>$B.t_s$</td>
</tr>
<tr>
<td>A finishes B</td>
<td>$A.t_s &lt; B.t_s &lt; A.t_e$ OR $B.t_s &lt; B.t_e$</td>
<td>$B.t_s$</td>
<td>$A.t_s &lt; B.t_s$</td>
<td>$B.t_s$</td>
</tr>
<tr>
<td>A contains B</td>
<td>$A.t_s &lt; B.t_s &lt; A.t_e$ OR $B.t_s &lt; B.t_e$</td>
<td>$B.t_s$</td>
<td>$A.t_s &lt; B.t_s$</td>
<td>$B.t_s$</td>
</tr>
</tbody>
</table>

Table 2: Low-Latency Analysis

Figure 3: Temporal Matching via Range Queries

The ordering of $t_d$ can implicitly be derived at $t_d$, because $t_3 < t_4$ and there are no timestamps beyond that. Furthermore, at $t_2$ and $t_2$ there are other relations sharing the same definitions up to that point, i.e., it is not possible to distinguish them from each other. To show this, we have grouped relations starting with $A.t_s$ as prefix groups in Table 2 ($B.t_s$ groups are analogous). For those reasons we can conclude $t_d(R) = t_3$.

A temporal constraint $C = (R_1, \ldots, R_k)$ for $A, B$ matches if at least one relation matches. Therefore, the earliest detection time is $t_d(C) = \{t_d(R_1), \ldots, t_d(R_k)\}$. Note that $t_d(C)$ is a set and the actual detection time of two situations depends on the fulfilled relations. Further, if $C$ contains all relations of a prefix group (cf. Table 2), the detection time of these relations is shifted to the trivial lower bound ($t_d(G)$).

Finally, for a pattern $P = (C_1, \ldots, C_m)$, each constraint must be matched. However, a single temporal configuration matching $P$ fulfills exactly one temporal relation $t_d(R)$ from each constraint, making $t_d(P) = \max(t_d(R) \in C_1, \ldots, t_d(R) \in C_m)$. In general, $t_d(P)$ is among the constraint detection points: $t_d(P) \subseteq \bigcup_{i=1}^{m} t_d(C_i)$.

5.3.2 Implementation. For the ease of presentation, we ignore the optional duration constraints on situations as well as prefix groups during the development and discuss the required changes at the end of this section. We gained two implementation-relevant insights from the low-latency analysis. First, new matches can only be detected if a new situation starts or a situation ends. Second, only a subset of the derived situations can possibly produce a match at $t_d(P)$. Thus, the matching process can be delayed until a situation with at least one endpoint in $t_d(P)$ occurs without affecting the latency. We call those situations trigger situations since only they should trigger a performMatch call. These insights affect our algorithms in the following ways. Situations must be available for matching from their start on, which can easily be achieved by adjusting the derivation. Additionally, we need to determine for each situation stream if the derived situations are trigger situations. For trigger situations we need to identify the point in time to execute performMatch (at its start, end or both).
Figure 4: Earliest detection time \( (t_d) \) of different temporal configurations for the same pattern finishes D OR C meets D. It defines situation A as starting point of every match. B is not explicitly related to C and D and required to happen after A. Consequently, B is a trigger situation and B.ts is in \( \ell_d(P) \). For D both D.ts (via meets) and D.te (via during, finishes) are in \( \ell_d(P) \). Figure 4 shows four representative temporal configurations for this pattern, highlighting the earliest point of detection \( (t_d) \). Configuration 1 showcases B as a trigger situation with \( t_d = B.ts \). For the second configuration, D is the trigger with \( t_d = D.ts \). This case also shows that two started relations may participate in a match if their end is unknown (B, D). The remaining configurations highlight D as a trigger, but with \( t_d = D.te \).

Instead of handling these cases explicitly, our low latency algorithm avoids them by ensuring a unique combination of situations in the working-set, before passing it to the matching algorithm. In particular, this means started situations are managed in a separate buffer, inaccessible for the matching algorithm, and all valid combinations among them (i.e., all combinations of started situations, not explicitly related to the current one) are built upfront inside the working-set. Furthermore, to avoid duplicate results, the following fact is exploited: temporal relations enforcing matching on a situation’s start require its counterpart to be finished in the past. On the other hand, temporal relations triggering matching on a situation’s end require its counterpart to be either started (and not yet finished) or finished at the same time (cf. Table 2). Consequently, manually adding the started counterpart to the working-set, before executing the matching algorithm on a situation’s end ensures uniqueness of the produced results.

The details are presented in Algorithm 4. After purging outdated situations from the buffers (Line 1), each started situation \( s \) is added to the additional buffer and if \( s.ts \in \ell_d(P) \), the algorithm performs a regular match with \( s \) being the only constant in the working-set (Lines 2-5). Furthermore, if there are started and unrelated situations, we perform matches with \( s \) and each combination of them (Lines 6-8). This accounts for configurations as seen in Figure 4. All finished situations are migrated to the regular buffer (Lines 9-11) and if \( s.te \in \ell_d(P) \), the matching process is triggered. This time with combinations of \( s \) and all started and related situations (Lines 15-16), further combined with all started and unrelated situations (Lines 17-18), which fuses the avoidance of duplicate results and false positives. An example for this case is shown in Figure 4.3. Note that, the actual constraint-checking among the created combinations is performed by the call to performMatch (Algorithm 3), since it is aware of pre-set situations in the working-set. As we will show in section 6, the extensive building of combinations has only minimal impact on the runtime-performance, because it shifts load from joining to the update algorithm and does not introduce additional computation steps.

Duration constraints on situations are incorporated into low latency-matching with only a few modifications: First, if a maximum duration constraint is defined (regardless of a possibly specified minimum duration), the corresponding situation must not be included in the matching process until its end is known – and the constraint is fulfilled. Hence, these situations are excluded from the set of started situations \( (S_s) \) and if their start timestamp is in \( \ell_d(P) \), matching is deferred to their end timestamp. Second, if a minimum but no maximum duration is defined, the inclusion into the set of started situations is deferred until the constraint is satisfied. This possibly implies the inclusion of its deferred start timestamp \( (s.ts) \) into \( \ell_d(P) \). As an example, consider the pattern A during B and the following order of timestamps: \( B.ts < A.ts < A.te < B.te \). This match cannot be detected at A.te, because B’s duration does not exceed the lower bound at this point. Hence B.te requires a matcher invocation.

To handle prefix groups the restriction that two started and explicitly related situations must not be matched is relaxed. That is, matching is performed if the corresponding temporal constraint contains one or more prefix groups. However, for still being able to omit false positives, the matcher must distinguish between prefix group and regular detection. Technically this means splitting the temporal constraint into two disjoint sets (one containing all temporal relations forming a prefix group and another one holding the remaining relations) and use the first set, when matching on a situation’s start and the second one on its end.

5.4 Computing the Evaluation Order

The matcher component maps the problem of temporal pattern matching to a multi-way join between situation buffers. Like multi-join processing in traditional relational database systems,
the performance of joining heavily depends on the order in which the join operations are executed. In this section, we discuss how the matcher’s evaluation order is computed and present the cost-model used during this process.

Analogous to classical join processing we implemented an optimizer that enumerates possible execution plans, computes the expected computational costs for each of them and suggests the most efficient plan for execution. We do not provide multiple implementations of the join operator, so that enumerating possible plans reduces to the enumeration of possible evaluation orders. To further reduce the number of plans to consider, we exclude orderings joining a situation buffer without an applicable temporal constraint. In other words: Plans involving the calculation of a cross product are omitted.

According to Equation 2, estimating the costs for a given plan boils down to estimating the size of intermediate results:

$$|R_i| := \begin{cases} |B_i| & \text{if } i = 1 \\ |R_{i-1}| \cdot |B_i| \cdot s_i & \text{otherwise} \end{cases}$$

(3)

$s_i$ denotes the selectivity of the applicable temporal constraints in step $i$ ($C_i$), which can be composed from the selectivities of the contained temporal relations as follows:

$$s_i := \prod_{C \in C_i} \left( \sum_{R \in C} |sR| \right)$$

(4)

When a query is initially deployed into the system, the situation buffers are empty and we have no estimation on the selectivity of the temporal constraints. Hence, we initially assume the selectivities depicted in Table 3. These values are backed by the following back-of-the-envelope calculation: The combined selectivity of all possible relations should be 100%. Assuming equal sized buffers and an equal temporal distribution of the situations, the selectivity of a before relation will be around 50%. For during, the number of results is limited by the maximum of both buffer sizes, because a situation $A$ can happen during at most one other situation ($B$), but $B$ may contain multiple $A$ situations. All other temporal relations define a 1:1 relationship, which limits the worst case to the minimum of both buffer sizes. As seen in Table 3, we additionally separate the last case by the number of stated equalities. Note that even though this is an initial estimate, the resulting plans prove to work well in most cases (cf. section 6.4.2).

5.4.1 Adaptivity. Once a query is deployed into a CEP-system, it is typically active for a long time. Hence, more important than the quality of an initial execution plan is the ability to tune this plan and adapt it to changing workloads. To do so, we keep track of the buffer sizes and selectivities imposed by temporal constraints during execution. The buffer-sizes are available at any point in time and at no cost, since they are tracked by the underlying data structure. However, to smooth out (potential) spikes, we monitor the buffer size using an exponential moving average, which is adjusted after each call to the matcher’s update method as follows:

$$EMA_i = \alpha \cdot |B_i| + (1 - \alpha) \cdot EMA_{i-1}$$

$EMA_i$ holds after the $i$-th update. $|B_i|$ denotes the size of the considered buffer at update $i$ and the smoothing factor $\alpha \in (0, 1)$ determines how much weight is given to previous values. For example, a value close to 1 assigns almost no weight to older values, while a value close to 0 decreases the influence of new values. The selectivities of the temporal constraints are also managed with EMAs using one EMA-value per constraint.

To check if a re-computation of the evaluation order is required, the active plan stores a snapshot of the statistics it is based on. After each update, we compare them to the current values and if any of them differs by more than the defined threshold ($t$), we trigger a re-computation.

Finally, if a migration is required, we are able to migrate to the new plan between any two involvements of the matcher component. Because the matcher does not store any intermediate results, but solely relies on the situation buffers this switch comes without any additional migration costs. As we will show in section 6.4.2, the total costs for adaptivity are negligible.

6 EXPERIMENTAL EVALUATION

In this section we present the results from our experimental evaluation of TPStream\textsuperscript{2}. First, we study TPStream’s evaluation performance in comparison to ISEQ and point based CEP systems. Then, we analyze the latency improvement of our approach in comparison to ISEQ. Finally, we prove the validity of our optimization techniques.

6.1 Setup

All experiments were conducted on a workstation equipped with an Intel i7-2600 3.4 GHz processor and 8GB of memory, running a Debian Linux (kernel version 4.11.11-1). The results presented for each experiment are averaged values from a total of 10 runs, whereby every run was preceded by a warm-up phase of evaluating at least 100,000 events before the measurement was started.

The main goal of this section is to compare TPStream’s processing performance and our low latency approach to the state-of-the-art solution for temporal pattern matching (ISEQ). There is no publicly available implementation of ISEQ, so we implemented it based on the available description in [20]. As required by the design of ISEQ, the input consists of interval streams ordered by endpoint. These streams are again generated with our deriv operator component.

In order to provide a comparison with point based systems, we also included CEP-solutions from the open-source community (Esper\textsuperscript{3} 6.0.1) and academia (SASE+ \textsuperscript{4}), when applicable. While Esper is a production ready CEP system, highly optimized for efficient query execution, SASE+ is one of the most popular CEP languages in the research community and served as foundation for the ISEQ operator. The rich query language of Esper allowed us to express both straw man’s approaches as sketched in the introduction. We refer to the first approach (2 phase pattern matching) with Esper-1 and the low latency approach is denoted as Esper-2. Because the SASE+ implementation does not feature chaining of queries, we only implemented the low-latency approach. TPStream and all its competitors are implemented in the JAVA programming language, whereby TPStream and ISEQ are based on JEPC [19] – an event processing middleware. We used

\textsuperscript{2}Datasets and source code available at http://uni-marburg.de/oaCPk
\textsuperscript{3}http://www.espertech.com
\textsuperscript{4}https://github.com/haopeng/sase

<table>
<thead>
<tr>
<th>Relation</th>
<th>before</th>
<th>during</th>
<th>overlaps</th>
<th>starts, finishes, meets</th>
<th>equal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Selectivity</td>
<td>0.445</td>
<td>0.03</td>
<td>0.01</td>
<td>0.0049</td>
<td>0.0006</td>
</tr>
</tbody>
</table>

Table 3: Initial estimates for the selectivity of temporal relations. Mirror relations are equivalent.
Processing Time

6.2.1 Aggressive Drivers. We injected different fractions (1M to 100M events) of the Linear Road dataset into the system and executed the example query of Listing 1 (without duration constraints). The thresholds for speeding, acceleration and deceleration were the 99th, 90th and 90th percentiles for the speed and positive/negative acceleration values of a 50M event sample. Besides chaining of queries, the SASE+ implementation also lacks support for disjunctions. Nevertheless, to include SASE+ in this experiment, we also evaluated a simplified query version which restricts the used temporal relations to meets and overlaps.

The results of this experiment are shown in Figure 5 (a – simplified pattern, b – full pattern). The x-axis shows the number of processed events, the processing time is shown on the y-axis.

6.2.2 Disconnected Pattern. The second experiment compares processing time and memory consumption of the systems using a pattern with high selectivity: A before B overlaps C. The difference to the first experiment is, that each A situation may be related to many B overlaps C sub-matches instead of contributing to at most one match. Hence, we expected the number of results and consequently the processing time/memory consumption to depend on the size of the configured time window.

We injected 300M synthetic events into the systems and executed

Oracle JDK 1.8.0.144 compile the systems and ran all experiments on that JVM with 6GB of heap space.

During the evaluation two data sources were used. The first source comprises trip data generated with the Linear Road Benchmark [4]. Besides other attributes, each event consists of a unique car id, its location, the current speed and acceleration. We generated data simulating 5 hours of traffic on a single expressway with 1000 active cars per hour. Each active car reports its state every second, leading to 887 million events (36 GB of data). The second source is a random event generator, tuned to pose high load on the system. It generates event streams with a configurable number of boolean attributes, each representing a single situation stream. The generated situations last between 10 and 100 seconds, while the gaps between two consecutive situations span 10 to 50 seconds (both uniformly distributed). Events are generated with a frequency of 1Hz, so that for a situation lasting n seconds, the corresponding attribute’s value is true for exactly n consecutive events.

Independent of the data-source, we used a single thread for both, reading/generating the data and evaluating the query. For each experiment, we measured the reading/generation time upfront and removed it from the presented results. The most important parameters throughout all experiments are as follows:

- **Event Rate** The rate (events/s) with which events are pushed into the systems.
- **Window Size** The size of the time window (s) during which a pattern must occur completely.
- **Event Count** The total number of events to process.
the query with window sizes varying from 500s (8:20 minutes) to 100,000s (slightly more than one day).

Figure 5 (c) shows the processing time of all systems as a function of the window size (note the log-scale). In this experiment, TPStream is able to outperform ISEQ by a factor of 14 using a window of 100,000s. This is because ISEQ does not make use of the order on the situations’ start timestamp and requires additional computational steps during result construction and buffer pruning. SASE+ did not finish this experiment in a reasonable time for none of the window sizes and Esper barely managed window sizes up to 20,000s. To measure the average memory consumption, we monitored the used heap space with a frequency of 20Hz during each run and averaged these values. Both, TPStream and ISEQ require only very little additional memory for increased window sizes: TPStream 911 - 1018 MB, ISEQ 903 - 1027 MB. Esper stays stable at 1 GB up to a window size of 10,000s but afterwards suffers from buffering single events rather than a compact representation like situations. For the last executable query (20,000s window) Esper already consumed 1.7 GB of memory.

6.2.3 Query Patterns. To give a comprehensive overview of TPStream’s processing performance, we evaluated 5 different query patterns and varied the number of situation streams from 4 to 10. Queries 1-3 (Equal, Meets, Chain) are of the form \( S_1 \oplus S_2 \oplus \ldots \oplus S_{n-1} \oplus S_n \), with \( \oplus = \text{equals}, \oplus = \text{meets} \) and \( \oplus \) a randomly drawn temporal relation, respectively. In query 4 (Star), \( S_1 \) is connected with every other situation, via a random temporal relation (i.e., \( S_1 \oplus S_2 \oplus S_3 \oplus \ldots \oplus S_{n-1} \oplus S_n \)). Query 5 (Combined) combines the two generic patterns by connecting the first \( n/2 \) situations via the Chain pattern and the remaining situations according to the Star pattern. Each query-type was executed 100 times, using 50M synthetic events and a window size of 2,000s.

The box plots in Figure 6 provide the median as well as the 25th and 75th percentiles of the processing time. For all query types, the median processing time increases linearly with the number of situations. The generic Chain pattern incurs higher maximum values than Equal and Meets, because the possible temporal relations include before, which is highly selective. This forces the matcher to build many partial results – especially if three or more consecutive situations are in a before relationship. Star queries are more sensitive to the concrete pattern instance, because in the worst case every situation triggers the matching process. This effect can also be observed for the Combined pattern, but to a smaller degree, because only half of the situations are connected via a Star pattern.

### 6.3 Low Latency

This set of experiments compares the result latency of our approach with the state-of-the-art solution for temporal pattern matching, ISEQ.

6.3.1 Application Time. At first, we measure the latency improvement of TPStream compared to ISEQ in terms of application time. That is, we compare the timestamps of the events that produced a result in both approaches and calculate their difference. We evaluated each temporal relation independently using two synthetic situation streams \((A, B)\). We varied the average duration ratio from 2:1 to 1:2, keeping A’s average duration fixed at 55 seconds. Note that the window size has no impact here (as long as it is not too small to hold a match), so it was set to 1,000s.

Figure 7 (a) shows the average latency improvements per temporal relation. For sequential relations (before, meets), the gain in latency is equal to the average duration of B situations, because matches are detected at B’s. For the remaining relations, the detection time is A’s and the average improvement depends on the concrete temporal relation. In the worst case (during) this is B’s duration/2. Note that, equals and finishes were not included, because no latency improvements can be achieved.

6.3.2 Wall Clock Latency. We conducted two experiments, showing that TPStream’s processing techniques significantly reduce the result latency in terms of wall clock time which is a critical aspect in a streaming scenario. Therefore, we repeat the experiment from section 6.2.2 twice: first, we measure the time passed between the arrival of the first event that could produce a result and the receipt of that result. We varied the window size and pushed events with the maximum possible rate. For the second experiment we fixed the window size at 100,000s and varied the event rate from 1M to 1 Events/s. This time, we split the measured latency in (i) processing latency: the time passed between arrival of the event that triggered the result and the actual receipt of that result and (ii) event latency: the time passed between arrival of the first event that could trigger the result and the arrival of the event that actually triggered that result.

The results are shown in Figure 7 (b,c). Both figures show the average latency per result (y-axis, note the log-scale for c). While (b) shows, that TPStream’s evaluation techniques provide latency savings through reduced processing time, (c) highlights the savings achieved with our low-latency matcher. Especially when the rate is in sync with application time (1 event/s), the event latency of ISEQ dominates the processing latency and almost reaches the application time savings (~35s, cf. Figure 7 a, 1:1, overlaps), while TPStream introduces no event latency at all.
6.4 Plan Quality & Adaption

Finally, we evaluate the optimization techniques presented in section 5.4. Like in section 6.2, events were pushed with the maximum possible rate.

6.4.1 Initial Plan Quality. To evaluate the quality of the generated initial plans, we used the following queries on three situation streams: Q1: A overlaps B AND A overlaps C AND B starts C, Q2: A overlaps B AND B before C AND B overlaps C and Q3: A before B AND A before C AND B before C. For each query, we generated all 6 valid plans and measured the throughput (processed events/s) by evaluating synthetic events with a window size of 5,000s.

Figure 8 (a) shows the results for the best, worst and suggested plans and clearly confirms our approach. For queries Q1 and Q2 the best plan was suggested. The initial plan for Q3 was C → B → A even though the estimated costs for C → A → B are the same. The experiments show that C → A → B would have been a slightly better choice, but the difference is negligible.

6.4.2 Dynamic Plan Adaption. To analyze the plan adaption capabilities of TPStream, we executed Q3 again and processed 300M events. The occurrence ratio of situations A, B and C changed from 1:1:1 to 1:50:50 after 100M events and finally to 1:1:1 after 200M events. The window size, smoothing-factor (a) and threshold for plan migration (t) were set to 10,000s, 0.01 and 0.2, respectively. Besides the adaptive implementation (TPS-A), we ran the experiment with both best initial plans C → B → A (TPS-1), C → A → B (TPS-2), and an implementation, doing a hard coded switch to the best plan exactly when the characteristics of the stream changes (TPS-O).

Figure 8 (b) shows the throughput for all four configurations and the three different stream-characteristics: TPS-1 and TPS-2 both have drawbacks in either one of the skewed phases, while our adaptive approach is very close to the optimal solution TPS-O (suffering slightly from dynamic adaption). However, the total runtime of TPS-O (63,523ms) compared to TPS-A (64,612ms) reveals only a negligible overhead of 1,089ms (less than 2%) for plan adaption.

7 CONCLUSION

We presented TPStream, a novel event processing operator for detecting complex temporal patterns among event streams. We enabled TPStream to derive lasting situations directly from streams of events and developed new techniques for detecting temporal patterns at the earliest possible point in time. Furthermore, we demonstrated low-cost adaptive approaches suitable for a streaming scenario. We proved the potential of TPStream by comparing it to industrial and academic solutions for CEP in experiments.

Since research on situations in CEP is scarce, we focused our efforts on presenting a fundamental solution suited for this scenario and equipped it with the capabilities to handle the adaptive, low-latency nature of stream processing. For future work, we intend to extend TPStream to tackle out-of-order arrivals [7, 21] and parallel processing [24, 26].

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REFERENCES